Novae as a Class of Transient X-ray Sources

K. Mukai[1,2], M. Orio[3,4,5] and M. Della Valle[5,6]

ABSTRACT

Motivated by the recently discovered class of faint (10^{34}–10^{35} ergs s^{-1}) X-ray transients in the Galactic Center region, we investigate the 2–10 keV properties of classical and recurrent novae. Existing data are consistent with the idea that all classical novae are transient X-ray sources with durations of months to years and peak luminosities in the 10^{34}–10^{35} ergs s^{-1} range. This makes classical novae a viable candidate class for the faint Galactic Center transients. We estimate the rate of classical novae within a 15 arcmin radius region centered on the Galactic Center (roughly the field of view of *XMM-Newton* observations centered on Sgr A*) to be $\sim$0.1 per year. Therefore, it is plausible that some of the Galactic Center transients that have been announced to date are unrecognized classical novae. The continuing monitoring of the Galactic Center region carried out by *Chandra* and *XMM-Newton* may therefore provide a new method to detect classical novae in this crowded and obscured region, where optical surveys are not, and can never hope to be, effective. Therefore, X-ray monitoring may provide the best means of testing the completeness of the current understanding of the nova populations.

Subject headings: stars: novae, cataclysmic variables — Galaxy: center — X-rays: binaries

[1]CRESST and X-ray Astrophysics Laboratory, NASA/GSFC, Greenbelt, MD 20771; mukai@milkyway.gsfc.nasa.gov

[2]Department of Physics, University of Maryland, Baltimore County, 1000 Hilltop Circle, Baltimore, MD 21250

[3]Department of Astronomy, University of Wisconsin, 475 North Charter Street, Madison, WI 53706; orio@astro.wisc.edu

[4]INAF – Osservatorio Astronomico di Padova, Vicolo dell' Osservatorio 5, I-35122 Padova, Italy

[5]Kavli Institute of Theoretical Physics, UC Santa Barbara, California 93106

[6]INAF, Osservatorio Astrofisico di Arcetri, Largo Enrico Fermi 5, 50125 Firenze, Italy; massimo@arcetri.astro.it

1. Introduction

Recently, several groups have reported their detections of relatively faint X-ray transients in the *Chandra* and *XMM-Newton* observations of the Galactic Center region (Porquet et al. 2005; Sakano et al. 2005; Muno et al. 2005). These authors conclude that these transients are collectively located near the Galactic Center, based on their absorbing columns and their sky distribution, although no direct distance measurements are available. With this assumption, the inferred luminosities of these transients are in the 10^{34}–10^{35} ergs s^{-1} range. The authors of these studies claim that such a luminosity is too high for cataclysmic variables (CVs), semi-detached binaries in which the accreting object is a white dwarf. Instead, they argue for neutron star or black hole accretors based solely on the luminosity. However, the Galactic Center transients are sub-luminous compared to the known transient populations of black hole or neutron star binaries (Sakano et al. 2005; Muno et al. 2005), requiring a new population (see, e.g., King & Wijnands 2006).

The accretion driven X-ray luminosities of CVs are indeed insufficient to explain the Galactic Center transients. Non-magnetic CV X-ray luminosities are in the range 10^{30}–10^{32} ergs s^{-1}, with the highest value being 3×10^{32} ergs s^{-1} for the old nova, V603 Aql (Baskill et al. 2005). Magnetic CVs, the intermediate polars (IPs) in particular, are more luminous in 2–10 keV X-rays, with estimated luminosities often exceeding 10^{33} ergs s^{-1} (Sazonov et al. 2006). However, since the highest luminosity recorded for an IP is 1.3×10^{34} ergs s^{-1} during the outbursts of the unusual IP (and another old nova), GK Per (Hellier et al. 2004), IPs are also not likely candidates for the Galactic Center X-ray transients.

However, the above discussion is incomplete because it is limited to the accretion driven X-ray luminosities of CVs. In reality, CVs can generate higher X-ray luminosities through nuclear fusion, which is a more efficient source of energy than accretion onto a white dwarf. Indeed, classical novae have been known to emit 2–10 keV X-rays at luminosities exceeding 10^{34} ergs s^{-1}. We present below a summary of X-ray properties of classical as well as recurrent novae.

2. Novae as X-ray Transients

A white dwarf accreting at below the critical rate will undergo a thermonuclear runaway and becomes a classical nova, once a sufficient amount of fresh fuel has been accumulated (see, e.g., Shara 1989 for a review). A classical nova releases enough energy ($\sim 10^{45}$ ergs) to eject a shell of up to $\sim 10^{-4}$ M$_\odot$ at a typical velocity of 1000 km s^{-1}. Classical novae are seen as spectacular optical transients that brighten by over 10 magnitudes, reaching peak

brightness as high as $M_v = -9$ (Della Valle & Livio 1995). By definition, a classical nova has only been observed to go into outburst once, although they are thought to repeat with a recurrence period of well over 1,000 years. A recurrent nova is a closely related system that has been seen to undergo multiple thermonuclear runaways; theories of thermonuclear runaways require a high mass white dwarf accreting at a high rate to explain the short recurrence times of these objects.

Imaging X-ray observations of classical novae weeks to months after visual peak have revealed at least two kinds of X-ray emission (Orio 2004). Of these, the supersoft emission peaks in the EUV/soft X-ray range with little or no flux above 1 keV. We do not discuss supersoft emission further in this paper, because supersoft emission is easily absorbed by the interstellar medium and is unobservable from sources in the Galactic Center region.

The other component is inferred to be from shocks within the ejected shell, although they are spatially unresolved within the first few years. The X-ray spectrum of the shell component can be modeled as optically thin thermal emission with temperatures in the 1–10 keV range in the early stages. The line-rich emission detected in some novae at a later stage are also likely to be from the shell, although they become too soft to be observable from the Galactic center region. The review by Orio (2004) has firmly established that some classical novae are 2–10 keV X-ray sources. We now attempt the first systematic survey to see how widespread this component is, and how bright they are on average.

We present a summary in Table 1 and Figure 1 compiled from the literature, as detailed below. We focus on the first 1,000 days since eruption. In the figure, we use labels such as "N1" defined in the table. For the three novae detected with *ROSAT*, we list their observed 0.2-2.4 keV luminosities and plot them in red. Their 2–10 keV luminosities are rather uncertain due to the mismatch with the *ROSAT* bandpass.

For other novae, we generally present the measured, absorbed 2–10 keV luminosity. Note that the values in Table 1 do not necessarily coincide with those that are reported in the references, sometimes because we have used more recent distance estimates, and because some papers report unabsorbed and/or bolometric luminosities.

Descriptions of the descriptions for the first 5 objects in Table 1 can be found in Orio (2004). Of the other novae observed with *XMM-Newton* or *Chandra*, the *XMM-Newton* detections of V2487 Oph (986 and 1187 days after outburst; Hernanz & Sala 2002) are thought to be of accretion driven X-rays, and hence we do not include these in our summary. More recently, V4633 Sgr has been detected with *XMM-Newton* (934, 1083, and 1265 days after outburst; Hernanz & Sala 2007). The authors favor a shell origin, although cannot completely exclude accretion origin, either. Our summary includes only the first point (the

other two, beyond our 1,000 day limit, are at similar levels but with larger error bars). This object is an exception in that we have used the unabsorbed 0.2–10 keV luminosity reported by Hernanz & Sala (2007). The spectral model consists of a soft and a hard component, so the 2–10 keV luminosity should be somewhat lower.

The remainder of classical novae are taken from the *Swift* survey of classical novae (Ness et al. 2007). As the focus of this paper is the supersoft component, they do not provide luminosities or the conversion factor appropriate for the shell X-rays. Since none of the *Swift* observations are deep enough to enable spectroscopy of the shell X-rays, we have used a single conversion rate of 6.24×10^{-14} ergs cm^{-2}s^{-1} (2–10 keV) per 1 *Swift* XRT cts ks^{-1}, appropriate for a kT=5 keV bremsstrahlung observed through $N_H = 1\times10^{22}$ cm^{-2}. Among the objects included in the Ness et al. (2007) compilation, we exclude V723 Cas, V1494 Aql and V4743 Sgr (observed only after day 1,000); V1047 Cen for which no distance estimate is available; and V574 Pup because its detections are dominated by the supersoft component.

This brief summary (see also Orio et al. 2001a; Orio 2004) leads to the following conclusion. These 2–10 keV X-rays from the ejected shells is a widespread phenomenon: of the 11 observations of 5 classical novae in the 2–10 keV band (i.e., excluding *ROSAT*) during day 10–100, all but one were detections at above 10^{33} ergs s^{-1}. The lone exception is the observation of V1188 Sco on day 98, with a relatively weak upper limit. These points are summarized in the form of two histograms (one for day 10–30, the other for day 30–100) of 2–10 keV luminosities of classical novae in Figure 2. The existing data are consistent with the hypothesis that all classical novae are transient 2–10 keV sources at above 10^{33} ergs s^{-1}. There are variations in the duration and peak luminosity from nova to nova, but some are known to exceed 10^{34} ergs s^{-1}. The case of V382 Vel suggests that there is a delay in hard X-ray turn-on of classical novae compared to the optical peak.

The range of plasma temperatures in the ejecta decrease from 20–30 keV at hard X-ray turn-on, to $\simeq$ 1 keV in a few months (e.g., Lloyd et al. 1992; Mukai & Ishida 2001). Within 1-2 years the nebula may have a rich line spectrum, emitting mostly below 1 keV (e.g., Ness et al. 2003, 2005). Of the novae discussed above, the time for the hard component of the X-ray emission to cool was about 6 months for the two fast novae (Balman et al. 1998; Mukai & Ishida 2001), but was longer (over 18 months) for slow novae with massive ejecta (Orio et al. 1996; Greiner et al. 2003), potentially exceeding the duration of the supersoft phase. However, the gradual decrease in temperature means that the duration of novae as >2 keV X-ray sources is effectively shorter than the total duration of novae as shell X-ray sources.

Even less is known of the X-ray emission from recurrent novae. IM Nor (R1 in Figure 1)

was not detected 1 month after outburst and was only a moderately strong ($\sim 2 \times 10^{32}$ $[d/1\ \mathrm{kpc}]^2$ $\mathrm{ergs\,s^{-1}}$) source 6 month past maximum (Orio et al. 2005). The hard component of CI Aql (R2) was detected 34 and 95 days after outburst at about $7{\times}10^{30}$ $\mathrm{ergs\,s^{-1}}$ (Greiner & di Stefano 2002) using the distance of 2.6 kpc (Lynch et al. 2004). In contrast, RS Oph (R3) reached a luminosity in excess of $>10^{35}$ $\mathrm{ergs\,s^{-1}}$ shortly after the outburst peak (Sokoloski et al. 2006; Bode et al. 2006). In Figure 1, we plot only the observed 2–10 keV luminosity from early *Swift* observations for RS Oph; *RXTE* measurements are similar. The fast turn-on and high luminosity of RS Oph is due to the existence of an M giant wind, which provides an additional mechanism for X-ray production not available in classical novae or to many recurrent novae, whose mass donors are on or near the main sequence. The relative paucity of X-ray data on recurrent novae reflects the fact that recurrent novae are much rarer than classical novae. In the rest of the paper, we will therefore concentrate on classical novae, but the possibility of an RS Oph-like transient near the Galactic Center region should be kept in mind.

3. Novae As Galactic Center Transients?

As our summary shows, novae are a known class of X-ray transients with peak luminosities above 10^{34} $\mathrm{ergs\,s^{-1}}$. Thus, they should be considered as a candidate class in discussing Galactic Center transients. In fact, novae are the only known class of transients with the right characteristics, as the known neutron star and black hole transients have much higher peak luminosities.

Classical novae can be found both in a relatively young population (e.g., the Galactic disk) and in the older population (e.g., the Galactic bulge). Della Valle & Duerbeck (1993) have shown (their Fig. 1) that the distribution of the rates of decline of classical novae in the Milky Way and in M31 perfectly overlap with each other, and both are statistically distinguishable from LMC distribution (which exhibits a predominance of fast rates of decline). Since it is well known from theoretical studies (e.g. Starrfield et al. 1985; Kovetz & Prialnik 1985; Livio 1992) that the rate of decline is a tracer of the mass of the white dwarf in the nova system, we can assume that the main bulk of the progenitors of novae in the Milky Way and in M31 originates in the same type of stellar population. Capaccioli et al. (1989) and Shafter & Irby (2001) have demonstrated that novae in M31 are mainly produced in the bulge (see also the tabulation of M31 novae by Pietsch et al. 2007), therefore in view of what is reported above, the same should occur for novae in our Galaxy.

A global Milky Way rate of $\sim$24 novae yr^{-1} has been measured by Della Valle & Livio (1994) by scaling from extragalactic nova surveys (Della Valle et al. 1994). A somewhat

larger estimate of $\sim$35 novae yr^{-1} has been obtained by Shafter (1997) by extrapolating from the current rate of nova discovery in the Galaxy (about 4–5 novae yr^{-1}) and by Darnley et al. (2006) based on a microlensing survey of M31. In the following we will adopt as an "educated" guess a global rate of 30 novae yr^{-1}, and estimate the rate of novae in a region of the sky within 15 arcmin of the Galactic Center. This is roughly the field of view of *XMM-Newton* EPIC observations centered on Sgr A*.

Recent estimates of the ratio nova_rate(disk)/nova_rate(bulge) range from 0.25 up to 0.40 (Capaccioli et al. 1989; Della Valle et al. 1992, 1994; Shafter & Irby 2001). By assuming from Ratnatunga & van den Berg (1989) a surface area for the Galactic disk of 850 kpc^2 and a typical scale height of 100 pc for disk novae (Della Valle & Livio 1998), the density of nova outburst in the Milky Way disk is $\rho_{\rm disk}$=0.4–0.7 $\times 10^{-10}$ novae pc^{-3}yr^{-1}. Assuming a distance from the Sun to the Galactic Center of 8 kpc, one can find that the rate of disk novae within 15 arcmin of the Galactic center is only 5×10^{-4} novae yr^{-1}. That is, Galactic Center X-ray transients are highly unlikely to be disk novae.

More uncertain is the estimate of the nova density in the bulge. Let us assume (from Figure 1 of Della Valle & Livio 1998) that most bulge novae are located within 400 pc of the Galactic plane. From Figure 2 of Shafter (1997) we can assume (rather optimistically) that most bulge novae occur within the first kpc from the Galactic center. Under these assumptions, we find that bulge novae are distributed within a prolate ellipsoid with a density of $\sim 3 \times 10^{-8}$ novae pc^{-3}yr^{-1}. The line of sight region within 15 arcmin of the Galactic center encompasses a volume of $\sim 35^2$ pc^2 $\times\ \pi \times 1000$ pc $= 3.8 \times 10^6$ pc^3. The expected number of bulge novae in this volume is therefore of order $\sim$0.1 novae yr^{-1}.

The majority of these novae go undiscovered. During 1978–1993, the average rate of discovery of Milky Way novae was 3.3 yr^{-1} (Liller & Mayer 1987). Even though the rate of discovery may have increased in recent years (about 6 yr^{-1} are reported in IAU Circulars since 2001), this still leaves of order 25 classical novae every year that are undiscovered. We expect that the undiscovered novae are preferentially located in crowded regions and/or behind high interstellar extinction. Both problems are extreme in the Galactic Center region. Therefore, optical observations are unlikely to yield a complete census of the novae in the Galactic Center region, although wide area IR monitoring should be able to do so.

There have been observations of the Galactic Center region roughly every 6 months with *XMM-Newton* for roughly 2 years between 2000 Sep and 2002 Oct, out of which three transients were discovered (Porquet et al. 2005; Sakano et al. 2005). To this, we add 1 year as the representative duration of novae as a Galactic Center X-ray transients (i.e., bright enough and hard enough to be detectable if they were placed at the Galactic Center; the precise value one adopts affects the following numbers only slightly). With this assumption,

these *XMM-Newton* observations should have been sensitive to novae that peaked optically between 1999 Sep and 2002 Oct, or a period of 3 years. Combined with the above estimate of 0.1 novae per year within 15 arcmin of the Galactic center, roughly the field-of-view of *XMM-Newton* EPIC cameras, we predict these observations should have detected 0.3 novae as X-ray transients. If this is the true expectation value, there is a 26% chance that at least one of the Galactic Center transients is a nova according to the Poisson distribution (4% chance that two or more were novae).

Most optimistically, then, one or two of the *XMM-Newton* discovered transients could have been unrecognized novae. On the other hand, it may well be the case that none of these transients are novae. Novae are poorer candidates for the *Chandra* transients, given the strong concentration of *Chandra* transients near Sgr A* (Muno et al. 2005). However, given the uncertainties involved both in the nova rate and the transient rate, we consider it advisable to keep novae in mind, particularly as regular monitoring of the Galactic Center region continues (Wijnands et al. 2006).

In fact, we can turn this argument around. There is a possibility that the present estimate of the Milky Way nova rate ($\sim$30 yr^{-1}) is underestimated, because optical monitoring is ineffective in the crowded, high extinction regions around the Galactic Center. The degree of central concentration of bulge novae is unknown; if there is an additional population of novae found preferentially near the Galactic Center, we would not know it from optical data. The continuing search for faint X-ray transients in the Galactic Center region can therefore be considered an important complementary method for discovering classical novae that are otherwise not recognized. Since the Galactic Center region is already regularly monitored with sensitive X-ray observatories for other purposes, it makes sense to utilize the existing data for this purpose.

4. Conclusions

Classical and recurrent novae are a known class of transient X-ray sources that reach luminosities in the 10^{34} – 10^{35} ergs s^{-1} range. The shell X-ray phase of novae may last months to several years, although they probably soften as they age, gradually making them less conspicuous above 2 keV.

Novae have the right spectral and temporal characteristics to explain some of the faint Galactic Center transients that have been detected with *Chandra* and with *XMM-Newton* in recent years. If the existing literature accurately reflects the rate of X-ray transients near the Galactic Center, then the known population of classical (and recurrent) novae are probably

a small, but not negligible, contributor to the overall transient population.

Muno et al. (2005) have argued that dynamical processes may lead to a high space density of X-ray binaries within 1 pc of the Galactic Center. That is, the concentration of X-ray emitters is forcing considerations of a new population of objects not seen elsewhere in the Galaxy. We propose that any such studies include white dwarf binaries, since Galactic Center specific processes could produce an additional population of novae beyond disk and bulge novae that are currently known. The combination of X-ray monitoring and population synthesis may represent our best hope of obtaining a complete picture of nova populations in the Galaxy, because optical surveys cannot possibly be effective in the Galactic Center region. Note that optical surveys fail to detect the majority of Galactic novae overall — compare the inferred Galactic nova rate of $\sim$30 yr^{-1} to the actual rate of discovery ($\sim$6 yr^{-1}).

Chandra and *XMM-Newton* have been monitoring the Galactic Center region more or less regularly over the last $\sim$8 years. Even at 0.1 novae per year within 15 arcmin of the Galactic Center, it is probable that a nova will be detected as a 2–10 keV X-ray transient soon, if one hasn't been already. A concurrent infrared monitoring campaign will be required, however, to prove beyond a reasonable doubt that a particular X-ray transient is due to a classical nova.

REFERENCES

Balman, S., Krautter, J. & Ögelman, H. 1998, ApJ 499, 395

Baskill, D. Wheatley, P.J. & Osborne, J.P. 2005, MNRAS, 357, 626

Bode, M.F., O'Brien, T.J., Osborne, J.P., Page, K.L., Senziani, F., Skinner, G.K., Starrfield, S., Ness, J.-U., Drake, J.J., Schwarz, G., Beardmore, A.P., Darnley, M.J., Eyres, S.P.S., Evans, A., Gehrels, N., Goad, M.R., Jean, P., Krautter, J. & Novara, G. 2006, ApJ, 652, 629

Capaccioli, M., Della Valle, M., D'Onofrio M. & Rosino, L. 1989, AJ, 97, 1622

Darnley, M.J., Bode, M.F., Kerins, E., Newsam, A.M., An, J., Baillon, P., Belokurov, V., Calchi Novati, S., Carr, B.J., Créz'e, M., Evans, N.W., Giraud-Héraud, Y., Gould, A., Hewett, P., Jetzer, Ph., Kaplan, J., Paulin-Henriksson, S., Smartt, S.J., Taspras, Y. & Weston, M. 2006, MNRAS, 369, 257

Della Valle, M., Bianchini, A., Livio, M. & Orio, M. 1992, A&A, 266, 232

Della Valle, M. & Duerbeck, H. 1993, A&A, 271, 175

Della Valle, M., Rosino, L., Bianchini, A. & Livio, M. 1994, A&A, 287, 403

Della Valle, M. & Livio, M. 1994, A&A, 286, 786

Della Valle, M. & Livio, M. 1995, ApJ,452, 704

Della Valle, M. & Livio, M. 1998, ApJ, 506, 818

Della Valle, M., Pasquini, L., Daou, D. & Williams, R.E. 2002, A&A, 390, 155

Greiner, J. & di Stefano, R. 2002, ApJ, 578, 59

Greiner, J., Orio, M. & Schartel, N. 2003, A&A, 405, 703

Hellier, C, Harmer, S. & Beardmore, A.P. 2004, MNRAS, 349, 710

Hernanz, M. & Sala, G. 2002, Science, 298, 393

Hernanz, M. & Sala, G. 2007, ApJ, 664, 467

King, A.R. & Wijnands, R. 2006, MNRAS 366, L31

Kovetz, A. & Prialnik, D. 1985, ApJ, 291, 812

Liller, W. & Mayer, B. 1987, PASP, 99, 606

Lipkin, Y., Leibowitz, E.M., Retter, A., & Shemmer, O. 2001, MNRAS, 328, 1169

Livio, M. 1992, ApJ, 393, 516

Lloyd, H.M., O'Brien, T.J., Bode, M.F., Predehl, P., Schmitt, J.H.M.M., Trümper, J., Watson, M.G. & Pounds, K.A. 1992, Nature, 356, 222

Lynch, D.K., Hackwell, J.A. & Russell, R.W. 1992, ApJ 398, 632

Lynch, D.K., Wilson, J.C., Rudy, R.J., Venturini, C., Mazuk, S., Miller, N.A. & Puetter, R.C. 2004, AJ, 127, 1089

Mukai, K. & Ishida, M 2001, ApJ, 551, 1024

Muno, M.P., Pfahl, E., Baganoff, F.K., Brandt, W.N., Ghez, A., Lu, J. & Morris, M.R. 2005, ApJ, 622, L113

Ness, J.-U., Starrfield, S., Burwitz, V., Wichmann, R., Hauschildt, P., Drake, J.J., Wagner, R.M., Bond, H.E., Krautter, J., Orio, M., Hernanz, M., Gehrz, R.D., Woodward, C.E., Butt, Y., Mukai, K., Balman, S. & Truran, J.W. 2003, ApJ, 594, 127

Ness, J.-U., Starrfield, S., Jordan, C., Krautter, J. & Schmitt, J.H.M. 2005, MNRAS, 364, 1015

Ness, J.-U., Schwarz, G.J., Retter, A., Starrfield, S., Schmitt, J.H.M.M., Gehreles, N., Burrows, D. & Osborne, J.P. 2007, ApJ, 663, 505

Orio, M., Balman, S., Della Valle, M., Gallagher, J. & Ögelman, H. 1996, 466, 410

Orio, M., Covington, J. & Ögelman, H 2001, A&A, 373, 542

Orio, M., Parmar, A., Benjamin, R., Amati, L., Frontera, F., Greiner, J., Ögelman, H., Mineo, T., Starrfield, S., Trussoni, E. 2001, MNRAS, 326, L13

Orio, M. 2004, in "IAU Colloquium 194: Compact Binaries in the Galaxy and Beyon," eds. G. Tovmassian & E. Simon, RevMexAA (Serie de Conferencias) 20, 182

Orio, M., Tepedelenlioglu, E., Starrfield, S., Woodward, C.E. & Della Valle, M. 2005, ApJ, 620, 938

Pietsch, W., Haberl, F., Sala, G. Steile, H., Hornoch, K., Riffeser, A., Fliri, J., Bender, R., Bühler, S., Burwitz, V., Greiner, J. & Seitz, S. 2007, A&A, 465, 375

Porquet, D., Grosso, N., Burwitz, V., Andronov, I.L., Ascehnbach, B., Predehl, P. & Warwick, R.S. 2005, A&A, 430, L9

Ratnatunga, K.U. & van den Bergh, S. 1989, ApJ, 343, 713

Rosino, L., Iijima, T., Rafanelli, P., Radovich, M., Esenoglu, H. & della Valle, M. 1994, A&A, 315, 463

Sakano, M., Warwick, R.S., Decourchelle, A. & Wang, Q.D. 2005, MNRAS, 357, 1211

Sazonov, S., Revnivtsev, M., Gilfanov, M., Churazov, E. & Sunyaev, R. 2006, A&A, 450, 117

Shafter, A.W. 1997, ApJ, 487, 226

Shafter, A. & Irby B. 2001, ApJ, 563, 749

Shara, M.M. 1989, PASP, 101, 5

Sokoloski, J., Luna, G.J.M., Mukai, K. & Kenyon, S.J. 2006, Nature, 442, 276

Starrfield, S., Sparks, W. & Truran, J. 1985, ApJ, 291, 136

Szkody, P. & Hoard, D.W. 1994, ApJ, 249, 857

Wijnands, R., in't Zand, J.J.M., Rupen, M., Maccarone, T., Homan, J., Cornelisse, R., Fender, R., Grindlay, J., van der Klis, M., Kuulkers, E., Markwardt, C.B., Miller-Jones, J.C.A. & Wang, Q.D. 2006, A&A, 449, 1117

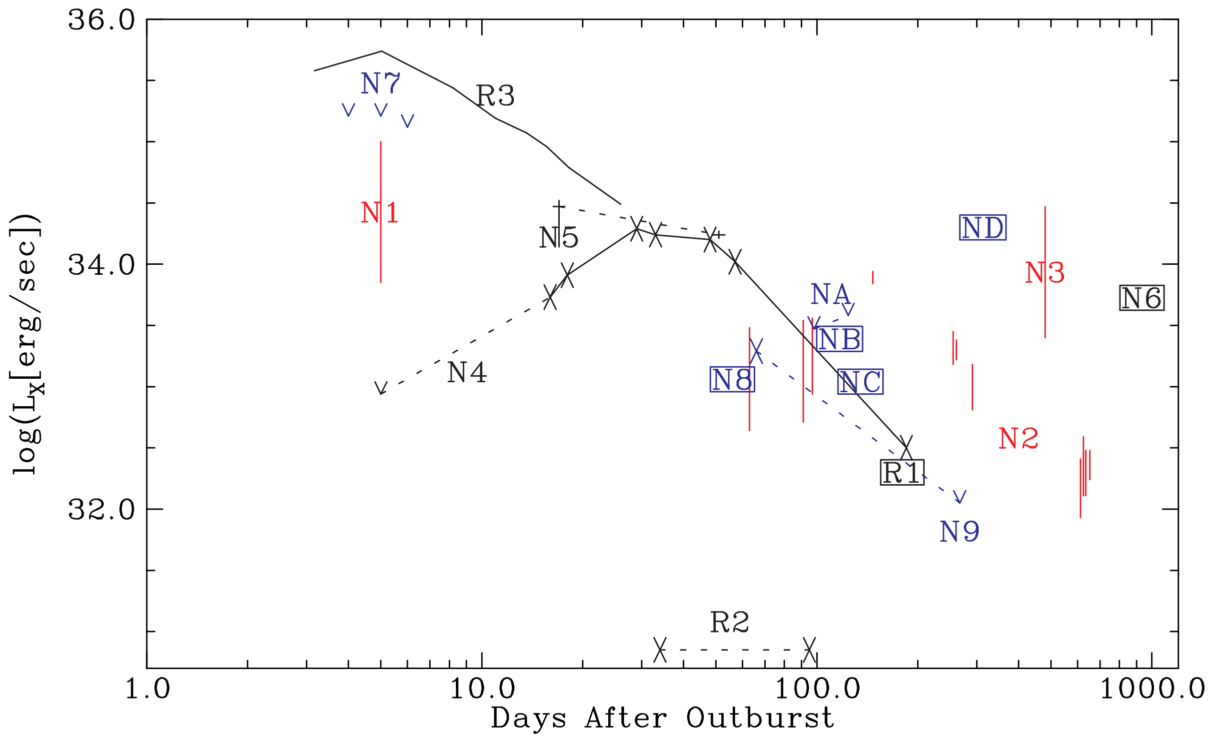

Fig. 1.— Hard X-ray light curves of classical novae, all shown against days since visual maximum. Black points are generally inferred 2–10 keV luminosities. Blue points are the same estimated from *Swift* XRT count rates, while red points are inferred 0.2–2.4 keV luminosities from *ROSAT* data. Points for any given object are connected, except that the 11 points for V1974 Cyg are left unconnected for clarity. Upper limits are shown as upside down carets; measurements are shown using a variety of symbols to allow those for different objects (indicated by the object keys, see below) to be distinguished. In 6 cases, object keys themselves, enclosed in boxes, are used to plot measurements. Classical novae plotted are: N1: V838 Her; N2: V1974 Cyg; N3: V351 Per; N4: V382 Vel; N5: Nova LMC 2000; N6: V4633 Sgr; N7: Nova LMC 2005; N8: V5116 Sgr; N9: V1663 Aql; NA: V1188 Sco; NB: V477 Sct; NC: V476 Sct; ND: V382 Nor. Recurrent novae plotted are: R1: IM Nor; R2: CI Aql; R3: RS Oph. See text for details.

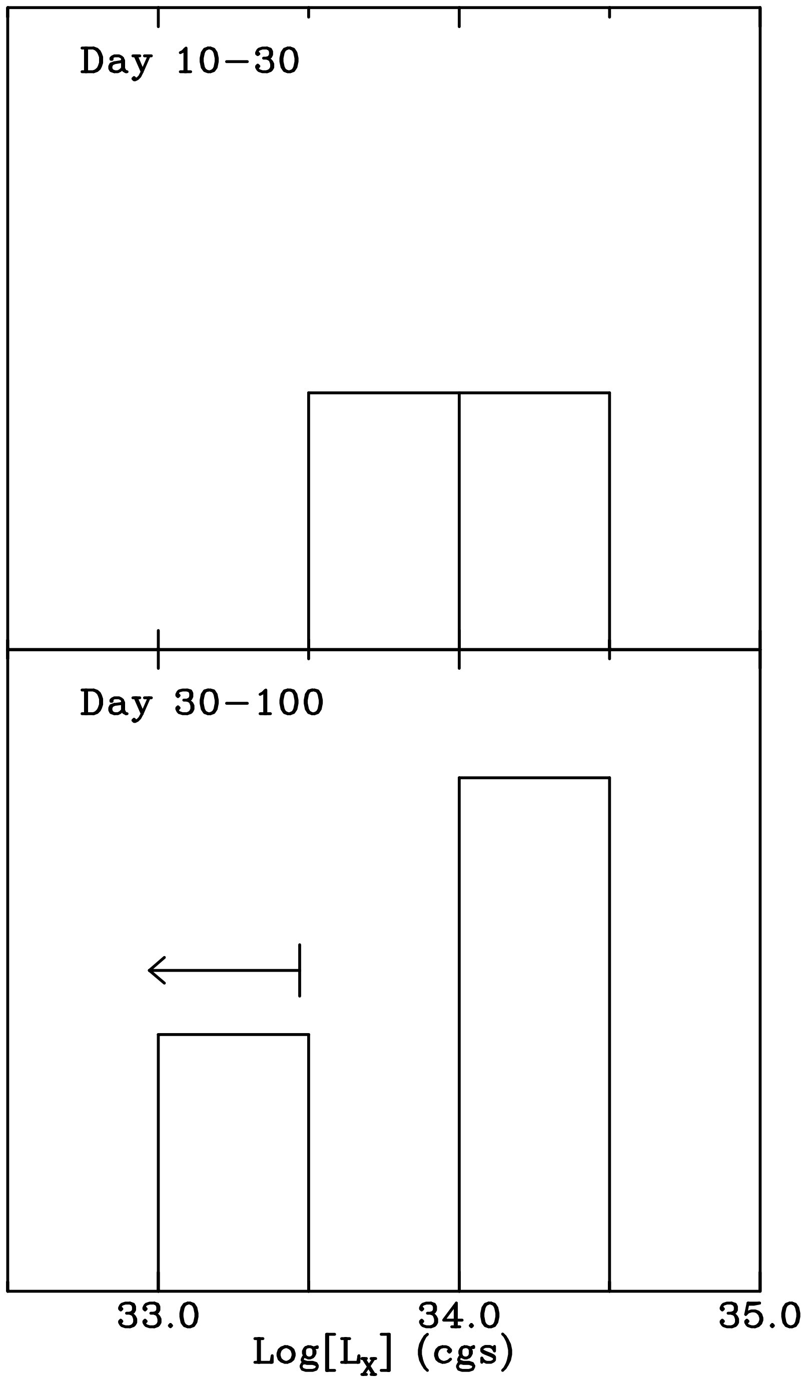

Fig. 2.— Histograms of 2–10 keV luminosities of classical novae during days 10-30 (top) and 30–100 (bottom). The top panel reports 4 independent detections of two novae, the bottom 6 detections of 4 objects and one upper limit for a 5th system.

Table 1. X-ray Observations of Classical Novae in Outburst

Nova	Dist. (kpc)	Obs.	Day	Log L_x (cgs)
V838 Her (N1)	3.4 [1]	*ROSAT*	5	33.85–35.00 [2]
		ROSAT	370	–[a]
		ROSAT	576	30.62–33.76 [3]
V1974 Cyg (N2)	1.9 [4]	*ROSAT*	63	32.64–33.48 [5]
		ROSAT	91	32.71–33.54 [5]
		ROSAT	97	32.94–33.56 [5]
		ROSAT	147	33.84–33.94 [5]
		ROSAT	255	33.18–33.45 [5]
		ROSAT	261	32.22–33.38 [5]
		ROSAT	291	32.81–33.18 [5]
		ROSAT	612	31.93–32.41 [5]
		ROSAT	624	32.11–32.59 [5]
		ROSAT	635	32.11–32.48 [5]
		ROSAT	653	32.24–32.48 [5]
V351 Pup (N3)	4.7 [6]	*ROSAT*	480	33.40–34.47 [6]
V382 Vel (N4)	1.7 [7]	*RXTE*	5	$<$32.94 [8]
		Beppo-SAX	16	33.63–33.83 [9]
		ASCA	18	33.81–34.01 [8]
		RXTE	29	34.19–34.39 [8]
		RXTE	33	34.14–34.34 [8]
		RXTE	48	34.10–34.30 [8]
		RXTE	57	33.92–34.12 [8]
		Beppo-SAX	185	32.40–32.60 [9]

Table 1—Continued

Nova	Dist. (kpc)	Obs.	Day	Log L_x (cgs)
N LMC 2000 (N5)	55	*XMM-Newton*	17	34.14–34.52 [10]
		XMM-Newton	51	34.21–34.27 [10]
		XMM-Newton	294	<32.92 [10]
V4633 Sgr (N6)	8.9 [11]	*XMM-Newton*	934	33.60–33.85 [12]
N LMC 2005 (N7)	55	*Swift*	4	<35.21 [13]
		Swift	5	<35.31 [13]
		Swift	6	<35.12 [13]
V5116 Sgr (N8)	11.3 [13]	*Swift*	56	32.28–33.32 [13]
V1663 Aql (N9)	5.5 [13]	*Swift*	66	33.08–33.43 [13]
		Swift	267	<32.05 [13]
V1188 Sco (NA)	7.5 [13]	*Swift*	98	<33.47 [13]
		Swift	124	<33.58 [13]
V477 Sct (NB)	11 [13]	*Swift*	117	33.24–33.50 [13]
		Swift	125	32.95–33.37 [13]
V476 Sct (NC)	4 [13]	*Swift*	135	<32.99 [13]
V382 Nor (ND)	13.8 [13]	*Swift*	313	34.23–34.36 [13]

References:[1] Lynch et al. (1992) [2] Lloyd et al. (1992) [3] Szkody & Hoard (1994) [4] Rosino et al. (1994) [5] Balman et al. (1998) [6] Orio et al. (1996) [7] Della Valle et al. (2002) [8] Mukai & Ishida (2001) [9] Orio et al. (2001b) [10] Greiner et al. (2003) [11] Lipkin et al. (2001) [12] Hernanz & Sala (2007) [13] Ness et al. (2007)

[a]Marginal detection but compatible with flux of the same order as on day 576